

Continuous Vacuum Drying of Whole Milk Foam. IV. Pilot Plant

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Abstract

This paper reports the operation of a pilot plant designed to produce engineering data for specification of a commercial size plant. Modifications to a small-scale continuous vacuum dehydrator necessary to adapt it to drying milk are described, with required inputs and control parameters given. Also, the physical dimensions of the auxiliary equipment components and their operating conditions for preparing the gas-concentrate foam from raw milk, with correct properties for drying, are outlined. The pilot plant was successfully operated for 42 one-shift periods at an average production rate of 6.95 kg per hour. An economic evaluation is to be given.

Introduction

A broad research program directed toward producing an economically feasible process for beverage-quality dry whole milk of easy dispersibility and adequate shelf life has been conducted in the Engineering and Development Laboratory of the Eastern Utilization Research and Development Division. Initially, it was demonstrated that a new dry whole milk, dried under high vacuum and low temperature in the form of an expanded spongelike structure, had unique properties of easy dispersion and natural flavor when reconstituted in cold water (8). This product retained its good dispersing properties during prolonged storage (4). It was further demonstrated that the principles of low-temperature processing with the exclusion of air could be translated to a continuous drying process while still retaining excellent dispersibility and initial flavor (2). Continued research showed that by modifying certain process variables, a limitation on production capacity, caused by low heat and mass transfer during drying while retaining a full foam structure, could be overcome through controlled foam subsidence (6). Extending the principle of exclusion of air in processing all the way to the final

package was found to result in retention of good flavor for almost a year when the product was stored at 4 C (1). Finally, an extensive study of the effects of the processing variables influencing product properties was completed. A set of operating conditions was determined which would overcome seasonally variable foaming characteristics of the milk and, thus, permit consistent year-round operation (3). This set of operating conditions was applied in a series of repetitive drying runs, to produce a quantity of material for a limited market test (7). Although various elements of the equipment used to produce vacuum dried whole milk have been described (1, 2, 6), this paper reports the integrated pilot plant as it was finally developed and used to produce the material for the market test.

Equipment

The final version of the integrated pilot plant is given schematically in Figure 1. Some of the equipment had to be built consistent with functional requirements and available materials and parts. The various internal dimensions were determined by balancing limiting factors such as: exclusion of air, avoidance of heat damage or spontaneous physical changes, transport properties, sanitation, and spacial arrangement. Wherever possible, construction and assembly were designed to permit in-place cleaning procedures.

1. *Homogenization-pasteurization.* Homogenization of the fluid milk was accomplished in a single-stage, two-pulsator machine, DeLaval Hydropulse Model No. P-2.² Its nominal capacity was 473 liters per hour at 175.8 kg/cm². Maximum working pressure was 281.2 kg/cm².

The pasteurizer was built as a heating-holding-heating section and a holding-two-stage cooling section with the homogenizer separating the two sections. The first heating unit was a shell and four-tube pass heat exchanger with 3.66 m of 14.1 mm id stainless steel tubing for the milk. The heating medium was low-pressure steam controlled manually through a pressure

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² Reference to certain products or companies does not imply an endorsement by the Department over others not mentioned.

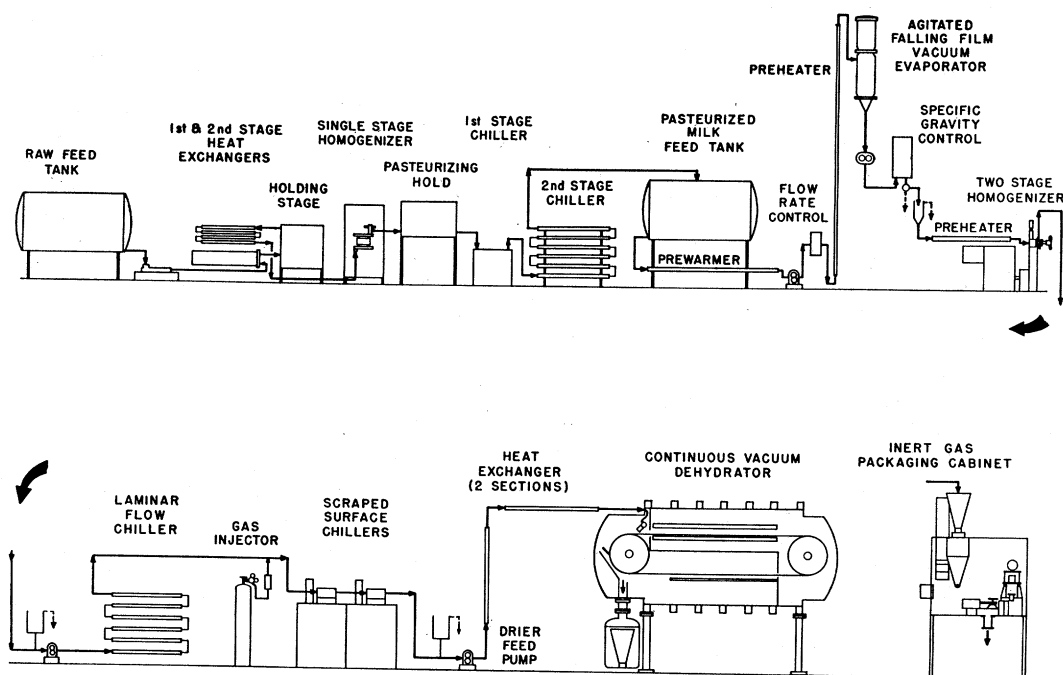


FIG. 1. Pilot plant schematic.

regulator valve. The first holding unit consisted of 9.45 m of 23.6 mm id sanitary tubing rolled into a coil, imbedded in insulation, and housed in a box. The second heating unit was a double pipe heat exchanger with 3.96 m of 10.9 mm id stainless steel tubing for the milk. The heating medium was hot water. The temperature-sensing element in the milk stream was located at the discharge of the homogenizer. The second holding unit consisted of 5.79 m of 23.6 mm id sanitary tubing, packed with insulation, housed in a box. The first cooling unit was a coil of 7.75 mm id stainless steel tubing, 13.71 m long, submerged in a pool of continuously overflowing, agitated water. The second cooling unit consisted of a double pipe heat exchanger with 6.71 m of 7.75 mm id stainless steel tubing. The cooling medium for the second cooling unit was a methanol solution circulating from a centrally located package chiller unit.

Feed was pumped to the homogenization-pasteurization equipment with a screw type pump (Moyno F-3).

2. Evaporation. Evaporation was performed in an agitated falling film vacuum evaporator (Rodney Hunt Turba-Film Model no. 1). The evaporating section was a vertical tube 20.32 cm id by 60.96 cm long. The vacuum in the evaporating section was maintained by control-

ling an air leak into the intake side of a mechanical vacuum pump. Heat was supplied by low-pressure steam controlled either manually or automatically. Vapors were condensed in the tubes of a shell and tube condenser of 7.80 m² condensing surface.

The evaporator was preceded by a double pipe heat exchanger with 2.13 m of 10.9 mm id stainless steel tubing as a prewarmer, a rotary gear metering pump with a capacity of 11 cc/rev (Zenith), and electromagnetic mass flow transmitter (Fischer-Porter Magmeter), and another double pipe heat exchanger with 3.96 m of 2.98 mm id stainless steel tubing as a preheater. Warm water and subatmospheric pressure steam were used as heating media, respectively.

The concentrate was removed from the bottom of the evaporator with a positive delivery pump (Waukesha Model DO-10) and directed through a specific gravity transmitter (Princo Densitrol). Concentrate viscosity was measured periodically with a Saybolt Viscosimeter having a Universal Tip bored to 2.18 mm.

3. Concentrate homogenization. The concentrate from the evaporator was homogenized in a two-stage, piston type homogenizer (Manton-Gaulin Laboratory Homogenizer Model 15M8-BA). This homogenizer had a variable speed drive which permitted rates between 9.5 and

56.8 liters per hour to be pumped. Maximum working pressure was 562.5 kg/cm².

Upstream from the homogenizer the milk concentrate passed through a double pipe heat exchanger with 1.22 m of 10.9 mm id stainless steel tubing. Subatmospheric steam was the heating medium.

4. *Gas dispersion-chilling.* Feed to scraped surface heat exchangers was metered by a rotary gear pump (Zenith no. 5) through a double pipe heat exchanger with 6.71 m of 7.75 mm id stainless steel tubing. Chilled water was used for cooling.

Between the double pipe exchanger and the first scraped surface heat exchanger a 1.39 mm id stainless steel tube was inserted into the line for inert gas (nitrogen) injection. Gas injection rate was controlled with a fine needle valve (Nupro Series S Cat No. SS-2S) downstream from an orifice type flowmeter (National Laboratories Vol-O-Flo).

The homogenized-chilled concentrate with entrained gas was further chilled and whipped simultaneously using two scraped surface heat exchangers (Votator Model FV314W) in series. Each had a rated hold-up of 30 sec at 56.8 liters per hour. The heat exchange surface of each was a 76.2 mm id cylinder, 30.5 cm long. The shaft rotating inside the cylinder was 57.15 mm od and had two scraper blades attached. Chilled water provided cooling here also.

5. *Dehydration.* Drying was accomplished in a continuous belt vacuum dehydrator (Chematron Corp. 1X2X2X9 Pilot Model Continuous Vacuum Dehydrator) (6) modified for vacuum foam drying of whole milk (Fig. 2). It consisted of an endless solid stainless steel belt 300 mm wide by 0.6 mm thick by 7.56 m long (Type 301 stainless ca.42 Rockwell C hardness

and standard 2B finish) tensed over heating and cooling drums. The drums were 0.61 m diameter by 0.36 m wide and were spaced 2.83 m apart. Either vacuum or pressure steam could be supplied to the heating drum, and coolant at various temperatures could be circulated through the cooling drum. Heat could be radiated to either side of the belt between the drums by means of three heat-radiating sections. There were 17 units of electric radiant heat rods individually controlled and located as follows: three units above the upper strand of belt (product side) and 14 units below the upper strand of belt. Each unit was composed of four rods arranged in two series pairs in parallel to each other. Each rod was rated at 800 w at 120 v (approximately 8.52 w per cm²) and was 33.0 cm long by 11.18 mm diameter with a heated length of 26.7 cm. The rods facing the product side of the upper strand of belt were spaced 16.2 cm apart and 14.0 cm from the belt. The rods facing the underside of the upper strand of belt were spaced 3.5 cm apart and 2.5 cm from the belt. Two units of steam-heated platens were located below the lower strand of belt (product side). These two units were 30.5 cm by 76.2 cm and 30.5 by 91.4 cm, and were located about 6.4 cm away from the belt. The whole apparatus was enclosed in a chamber where pressure could be maintained from 50 to 1.0 mm Hg abs. The pressure was monitored with a capacitance diaphragm pressure gauge (MKS Instruments Inc. "Baratron"). The vacuum pump was a multi-stage steam jet eductor. The speed of the belt could be varied between 1.58 and 22.8 meters per minute.

The interior of the chamber was partitioned in two parts to separate the area where the bulk of the water was removed from the area where

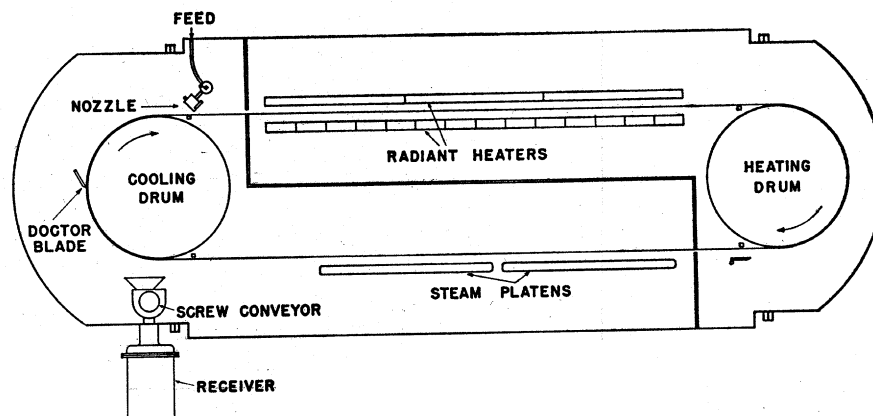


Fig. 2. Dryer schematic.

drying was finished and the product cooled and removed (Fig. 2).

The material to be dried was laid in a continuous ribbon on the belt by a nozzle designed to give a thin, wide sheet on the belt (2) (Fig. 3). The nozzle was a rectangular chamber whose front face was adjustable with shims to give the desired opening. The shims were also shaped so that smooth edges of thickness uniform with the rest of the ribbon would be formed. The nozzle was tilted at a 45-degree angle to reduce tearing the foam ribbon. Feed to the nozzle was pumped through a double pipe heat exchanger with 3.05 m of 10.7 mm id stainless steel tubing in two sections. The feed pump was a rotary gear type (Zenith no. 5). Cooling medium was chilled water.

The dried residue was scraped from the belt with a stainless steel doctor blade mounted on a holder much like a blade in a safety razor (Fig. 4). The doctor blade was of Sandvik 11R51 stainless steel 22.2 mm wide by 292.1 mm long by 0.30 mm thick. The holder was stationed at about a 40-degree angle to the tangent to the belt at the point of contact. The blade was held against the belt by hydraulic cylinders, with the holder travel restricted by stops. When engaged, the blade bent slightly and assumed about a 28-degree angle to the tangent at the point of contact during operation. The product dropped into a screw conveyor which discharged it to alternate receivers. Inner transportable containers within the receivers permitted removal of product to the packaging facilities without air contamination (1).

6. *Packaging.* The dried product was packaged in an inert atmosphere cabinet designed to give an atmosphere consistently below 0.01% in oxygen. The cabinet was equipped with a screening-comminuting device which reduced particles too large to fall through a 20-mesh

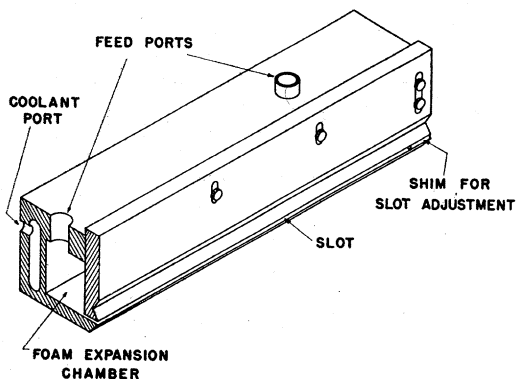


FIG. 3. Nozzle cut-away.

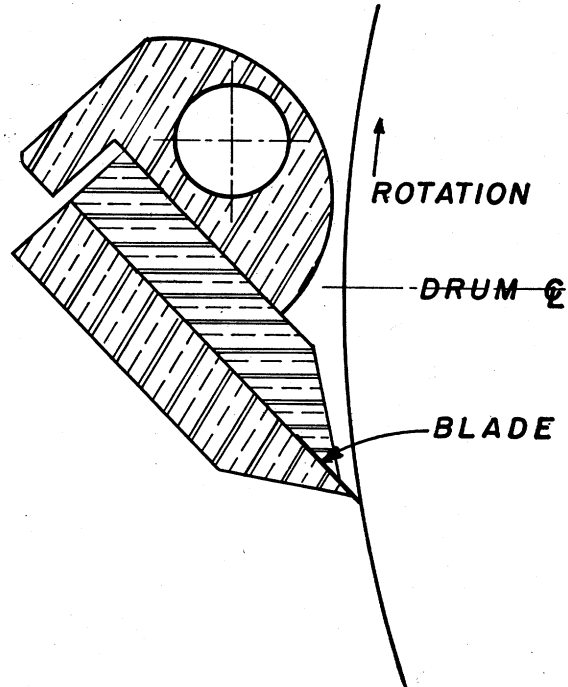


FIG. 4. Doctor blade cut-away.

screen. The cabinet also had facilities for introducing, filling, weighing, sealing, and removing cans.

Operation

A typical experimental production trial is described. For ready understanding of it, reference should be made to the flow diagram (Fig. 1), analyses of raw materials, intermediates and product (Table 1), and operating data (Tables 2 and 3). A trial run required two working days for completion. On the first day the milk to be dried was received and processed up to evaporator feed. Meanwhile, the remainder of the pilot plant underwent thorough cleaning and sanitizing procedures. On the second day the partially processed milk was fed forward to final processing and packaging while the equipment used the first day was sanitized.

Raw whole milk was held at 10 C in a 300-gal dairy type farm bulk tank. Necessary additions of lecithin, to produce more uniformity in season-to-season foaming characteristics (Central Soya, Inc., Centrophil SG) (2), and vitamin D concentrate in accordance with standard practice were made (Table 1). The homogenization-pasteurization equipment was brought close to operating temperature on water. The switchover to milk was made and as the milk was processed it was directed to another dairy-

TABLE 1. Analyses of raw materials, intermediates and product.

Raw milk feed		Average (min to max) specification	
Solids (%)		11.92 (11.59 to 12.33)	
Fat (%)		3.163 (2.87 to 3.34)	
Lecithin added (%) MFB		.0850 (.0831 to .0867)	0.084
Vitamin D concn added, USP units/qt		400	
Evaporated concentrate			
Solids (%)		45.3 (44.4 to 46.4)	
Specific gravity		1.110 (1.098 to 1.116)	
Viscosity, stokes (cm ² /sec)		349.3 (324.2 to 376.2)	353.0
Dryer feed			
Specific gravity		0.916 (0.902 to 0.954)	0.915
Product			
Moisture (%)	(a)	4.10 (3.6 to 4.8)	< 4.5
HMF, μ moles/liter	(b)	0.85 (0 to 2.4)	< 2.0
Bulk density (g/ml)	(c)	0.40 (0.34 to 0.45)	> 0.34
Insoluble floating solids (% MFB)	(d)	1.87 (1.33 to 2.47)	~
Solubility index (ml)	(e)	< 0.10	< 0.5
Flavor score	(f)	38.9 (38.2 to 39.5)	> 36.0
Milk fat content (% MFB)	(g)	26.4 (24.3 to 27.6)	26.0

^a By toluene distillation per E. S. DellaMonica et al., J. Dairy Sci., 51: 40. 1968.

^b As described by E. S. DellaMonica et al., J. Dairy Sci., 51: 352. 1968.

^c Packed by tapping.

^d E. S. DellaMonica, personal communication.

^e As described by American Dry Milk Institute, Chicago, Illinois.

^f Modified form of the 0 to 45 Scoring Test adopted by American Dairy Science Association (1).

^g As described by O. S. Sager and G. P. Sanders. A BDI detergent test for milk fat in milk and other dairy products. Proc. 45th Conv. Milk Ind. Found., 4: 29. 1952.

type farm bulk tank for further chilling and overnight storage. Pasteurizing and homogenizing were interrupted by addition of a holding stage in the preheat section. This holding stage increased the amount of milk fat that would be molten during homogenization.

The next day processing began with the milk being directed to the evaporator feed pump through the prewarmer. Increasing the temperature resulted in relatively low back pressure on the feed pump due to the reduction in viscosity. The feed pump delivered the milk to the evaporator through the preheater which brought the milk up to the temperature of evaporation. Feed rate was controlled by the mass flow transmitter between the pump and preheater. As evaporation proceeded the specific gravity and viscosity of the concentrate were monitored. During startup, adjustments were made manually in the steam to the jacket. When viscosity was substantially correct the control of jacket steam was switched over to automatic, based on specific gravity which was a more convenient measurement for continuous control. Periodic monitoring of viscosity was

continued. Although there was no reliable correlation found between solids and viscosity from batch to batch of milk, within a given batch a suitable correlation did exist for adequate control of viscosity by specific gravity.

The concentrate was then directed to the concentrate homogenizer after passing through the heat exchanger. Heating to 57.2 C before homogenization was in accordance with standard practice. Homogenization at 210.9 and 35.15 kg/cm² was found to prevent "oiling off" and clumping of the fat after product reconstitution. The homogenizer pumped the concentrate to a metering pump with a backup reservoir. The metering pump fed the milk forward, first through the laminar flow chiller, then to the point of gas injection, and then through the two scraped surface coolers. The laminar flow chiller reduced the temperature below that which promotes churning. The scraped surface heat exchangers not only fixed the temperature of the concentrate required at this point, but also whipped the concentrate-gas mixture into a system of sufficient homogeneous stability for the drying process. The impetus of the meter-

ing pump finally delivered the mixture to the dryer feed pump with backup reservoir. The dryer feed pump in turn delivered the gassed concentrate into the feed nozzle inside the dryer through a final heat exchanger, wherein the temperature of the feed to the nozzle was fixed. Within the nozzle the gassed concentrate expanded. It then issued as a thin wide ribbon of foam and was laid on the belt.

As the feed concentrate was being prepared the dehydrator was prewarmed for about 30 to 45 min. This prewarming permitted the collection of acceptable product within 5 to 10 min after the milk was introduced into the dryer. Also, a small quantity of nitrogen gas was admitted into the lower left portion of the chamber. Thus, the atmosphere in the dryer during drying was composed of nitrogen and water vapor, with air and oxygen reduced to an inconsequential level (5).

When the product receiver liners were filled they were isolated, vented with nitrogen, and transported to the inert atmosphere packaging cabinet.

Results and Discussion

The evaluation of the continuous vacuum dehydrator as a dryer for whole milk had two objectives: first, to appraise the capability of the equipment to produce a beverage-quality dry whole milk with variable properties of raw milk inherent in routine day-to-day operation; and second, to accumulate data and experience as a basis for specifications for a full-scale plant.

A series of 42 repetitive one-shift trials were made with these objectives in mind. Operating conditions and calculated capacities are shown in Tables 2 and 3. The average production rate of dry whole milk was 6.95 kg/hr. In these trials it was intended to operate with the same set of conditions each day and observe the effects of variability of the raw material on product quality. The variability in properties of the product that resulted, shown in Table 1, was considered within acceptable limits. This variability was attributed not only to the natural variability of the raw material but also to

TABLE 2. Operating data for dryer feed preparation.

Pasteurization-homogenization	Value
First-stage heating temperatures in/out (C)	10.0/60.0
Fat-melting hold time (sec)	31
Second-stage heating temperatures in/out (C)	57.2/71.1
Homogenization pressure (kg/cm ²)	210.9
Pasteurizing hold temperatures in/out (C)	73.9/72.2
Pasteurizing hold time (sec)	19
First-stage cooling temperature out (C)	32.2
Second-stage cooling temperature out (C)	12.8
Flow rate (kg/hr)	456
Evaporation	
First-stage warming temperatures in/out (C)	1.7/14.4
Second-stage preheating temperatures in/out (C)	14.4/51.7
Feed rate to evaporator (kg/hr)	93.9
Evaporation temperature and pressure (C/mm Hg abs)	51.7/100
Agitator speed (rpm)	1450
Concentrate rate from evaporator (kg/hr)	24.9
Concentrate homogenization	
Concentrate warming temperatures in/out (C)	48.9/57.2
Concentrate homogenizing pressures (kg/cm ²)	210.9/35.15
Chilling-gas dispersion	
Laminar flow chill temperatures in/out (C)	54.4/12.8
Concentrate flow rate (liters/min)	0.25
Gas injection rate (liters/min)	0.05
Scraped surface exchangers rotor speed (rpm)	650
Scraped surface exchangers temperatures in/out (C)	12.8/10.0-0 ^a
Final stage cooling temperatures in/out (C)	10.0-0/72 ^a

^a Temperature variable—selected after observing foam behavior during drying.

the difficulties of precise control inherent in this scale of operation.

The degree of foam subsidence during drying would vary from batch to batch, due to variable foaming characteristics. The operator could influence foam subsidence directly by carefully controlled adjustments in the temperature of gas dispersion in the scraped surface heat exchangers, other parameters being essentially constant.

Extended operation beyond one shift was not explored. Commercial scale vacuum dehydrators are operated successfully for upwards of 120 hr consecutively per week, and it is anticipated they will perform similarly with milk.

TABLE 3. Dehydrator operating data.

Item	Value
Nozzle aperture (cm)	.075
Chamber pressure (mm Hg abs)	18.95
Belt speed (m/min)	4.83
Surface temperature of radiant heat rods	
First zone belt side (C)	670 ^a
Surface temperature of radiant heat rods	
First zone product side (C)	650 ^b
Hot drum condensate temperature (C)	75.8 ^c
Steam to third zone platens (kg/cm ²)	7.0
Inert gas bleed to dry side of partition	
0.6 (kg/hr)	0.6
Cooling drum coolant temperature (C)	-2.2 ^d
Temperature of belt as it leaves	
cold drum (C)	7.2 ^e
Concentrate flow rate to nozzle (kg/hr)	14.74
Concentrate temperature into nozzle (C)	7.2
Concentrate gas content (cc/liter of ungasged cone)	205 ^f

^a Average power input in volts/amps was 115/5.70/unit.

^b Average power input in volts/amps was 155/8.40/unit.

^c Corresponds to about 300 mm Hg abs pressure.

^d Adjusted to satisfy (e).

^e Should not be more than concentrate temperature.

^f Corresponds to about 0.915 sp gr in dryer feed.

The component with the shortest operating period probably would be the evaporator, due

to fouling, and this would necessitate installation of multiple evaporators for long-time processing.

The continuous vacuum dehydrator has been shown capable of producing an acceptable beverage-quality dry whole milk over a period extending from mid-January to mid-May 1968. Economic evaluation of the process and translation to commercial scale is the subject of a forthcoming paper.

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